3.0 MEASUREMENT METHODS

The stage (i.e., height) of water in a stream can be readily measured at some point along a stream reach with a staff gage or water level recorder. Conversion of stage to a discharge rate, or quantity of flow per unit time, can then be accomplished by stream gaging or the use of precalibrated flow measurement devices. Section 3.1 presents the use of gages for measuring and recording stage in relation to calculating discharge. Sections 3.2 and 3.3 describe the use of pre-calibrated weirs and flumes, including the appropriate use for each measurement method, and describes how the measurements are made. The remaining sections describe non-structural flow measurement devices, such as current meters, acoustic flow meters, and the application of tracers and dye dilution methods. Each section, in addition to a description of the measurement devices, discusses siting criteria for the particular devices, the importance of site selection for obtaining accurate measurements, and the applicability of the method.

3.1 GAGES

The gage is the part of the water measurement structure (e.g., weir, flume) that measures stage height, or stage height and velocity, for input into the equation to calculate discharge. Gages can also exist separate from a physical structure. A staff gage, for example, could be attached to a bridge piling and use the channel itself as the measuring structure.

Gages are either non-recording or recording types. Recording gages keep track of stage levels at preset intervals and non-recording gages require an observer to read stage height from the gage. Non-recording gages have the advantage of low initial costs and relatively simple installation. However, non-recording gages require an field observer to take regular measurements. Over time, accuracy and precision may be enhanced with a recording gage. Recording gages eliminate the need for regular field observation and allow collection of reliable, long-term stage records. Non-recording gages are discussed in Section 3.1.2 and recording gages in Section 3.1.3.

3.1.1 General Criteria for Selecting Sites to Establish Gages

Water measurement sites are typically selected after a thorough reconnaissance of the area; including examination of geologic, topographic, and other maps of the area. Tentative sites are marked on maps and the stream characteristics are examined in the field. Carter and Davidian (1968) outline basic factors to be considered when choosing a site for measuring flow. These basic factors are general siting considerations that are applicable to all measurement approaches discussed in this guidebook.

- Channel characteristics should be such that a fixed and permanent relationship can be established between stage and discharge. Good measurement sites are often located in reaches with critical or sub-critical flow (e.g., immediately upstream of riffles or falls).

- Sites that experience backwater conditions should be avoided. Poor measurement conditions occur when backwater submerges measurement structures. Backwater conditions can result from downstream tributaries, lakes, channel constrictions, tailings ponds, storm water ponds or other sources.

- The channel cross section should be known or measurable by survey, and geomorphologically stable to ensure quantification of an accurate stage-discharge relationship.

- Flow should not bypass the site in ground water (i.e., intermittent conditions), or side channels. Measurement errors can also occur in reaches where significant flow occurs through alluvial gravels in the substrate. This is often a problem at mine sites because mines are often located in remote mountainous areas where channel substrates often are composed of large cobbles and gravels. Under these conditions, accurate flow measurements can be obtained using dye-dilution or tracers methods (see Section 3.6).
- The site should be accessible under reasonably foreseeable flow and weather conditions.

3.1.2 Non-Recording Gages

A reliable record of stage can be obtained through systematic observation of a non-recording gage by a trained observer. Factors to consider when making the choice to rely on a non-recording gage include:

- Site accessibility.
- Weather.
- Length of data collection.
- Regularity of data collection.
- Hydrologic variability.

Generally, a recording gage should be selected for use at mine sites, with a non-recording back-up, unless the site is easily accessed under all weather conditions. Non-recording gages could be used if only periodic measurements are necessary or cost is a driving factor. Site access to remote gages at mine sites is often difficult. Non-recording gages will tend to miss storm driven, peak flow, or other unique events unless the observer happens to be taking readings when the event occurs. It is often impractical in remote mine areas to travel to important sites to obtain flow measurements during storm events.

Common types of non-recording gages are staff, wire-weight, float-tape, and electric-tape. These gages are described in detail below.

Staff Gage

A staff gage is used to read stage height and is a common component of most gaging stations or measurement programs. The United States Geological Survey (USGS) vertical staff gage is considered the standard. The USGS staff gage is made from one or more porcelain enameled iron sections. Each section is 4 inches wide and 3.4 feet long with measurements every 0.02 feet.

Staff gages are installed in either a vertical or inclined alignment. Vertical staff gages are commonly used as reference gages in stilling wells or as a backup gage situated in the channel outside the stilling well. Vertical staff gages can be installed on bridge pilings or other permanent, fixed structures in the river channel, providing that channel geometry is understood. Knowledge of the channel cross-section allows stage height, as measured on the staff gage, to be converted to discharge using either Manning's equation, or using a specific stage-discharge relationship if one has been developed. Inclined staff gages are constructed from heavy timber and securely attached to some permanent foundation. Inclined staff gages are less susceptible to damage by floods and floating debris because they are flush against the streambank (Buchanan and Somers, 1982).

Wire-Weight Gage

The standard type A wire-weight gage consists of a drum wound with a single layer of cable, a bronze weight attached to the end of the cable, a graduated disc, and a Veeder counter. The disc is graduated in tenths and hundredths of a foot and is permanently connected to the Veeder counter. The bronze weight is lowered until it touches the water surface. Stage is measured as a combined reading of the counter and the graduated disc (Buchanan and Somers, 1982).

Float-Tape Gage

The float-tape gage consists of a float, a graduated steel tape, a counterweight, and a pulley. The float is attached to one end of the graduated steel tape and the counterweight is attached to the other. The float is typically a 10-inch diameter copper float that rests on the water surface and is kept in place by the counterweight. Float-tape gages are commonly found inside stilling wells (Buchanan and Somers, 1982).

Electric-Tape Gage

Electric-tape gages consist of a graduated steel tape fastened to a weight, a reel for the tape, a battery, and a voltmeter or buzzer. The tape is lowered until it contacts the water surface. Contact with the water surface completes the electronic circuit and produces a signal to the voltmeter or buzzer. Electric-tape gages are typically used for measuring stage height in stilling wells or shallow ground water wells. These gages are occasionally used outside and can be particularly useful if oil is floating on the water surface. The electric-tape gage can be used to measure the oil/water interface due to the fact that oil is a dielectric (Buchanan and Somers, 1982).

3.1.3 Recording Gages

Recording gages automatically track changes in the water surface with respect to time, eliminating the need for regular site visits to read the gage. Recording gages can also be relied upon to capture more variability in the range of discharges, including extreme events, because water level is being continuously recorded or recorded at regular intervals. The two common types of water stage recorders are analogue or graphic, and digital. The analogue recorder has been used extensively since the early part of the twentieth century; however, digital recorders are becoming increasingly common. While the digital recorder is replacing the analogue, neither system is foolproof. Both systems should be installed, with the analogue as a back-up, at particularly important or sensitive sites (British Columbia, 1998).

Water stage recorders can either be connected to a float located in a stilling well or to a bubbler or submersible pressure sensor. The stilling well is fastened to the channel bottom or water measurement device; intake pipes ensure that the water level in the stilling well is equal to the water level in the channel or measuring device. Stilling wells are used, instead of measuring stage directly off the water surface, to protect the stage recorder and minimize fluctuations in the water surface caused by wind and waves. The bottom of the stilling well must be lower than the minimum anticipated stage and the top above the maximum expected stage. Intakes should be properly sized to prevent lag during rapid stage changes and prevent velocity-head effects in the stilling well. Bubbler or submersible pressure sensors do not require the use of a stilling well. These devices are not affected by small fluctuations in water surface elevation caused by wind or waves because they rely on pressure (i.e., head) measurements taken inside the water column. Accuracy of these devices, however, can be affected by changes in barometric pressure.

Digital Recorder

Digital recorders use electronic sensors and data loggers to record and store water level information in database ready digital format. Data can be downloaded from the data logger to a personal computer for easier, faster, and more accurate compilation of recorded values. Digital recorder technology has progressed to the point where data on water quality and meteorology, in addition to water level, can be collected with a single recorder (British Columbia, 1998). Digital recorders can also be set up for remote access via telephone or the internet. Several varieties of digital recorders are available, including ultrasonic level sensors, submersible pressure sensors, and pressure measurement sensors or bubbler gages.

Ultrasonic sensors send out a series of sound waves through the air, the sound waves strike the water surface and bounce back to the sensor. Total transit time from the sensor to the water surface and back is related to the distance traveled and water stage. Ultrasonic sensors are non-invasive, requiring no physical contact with the channel being measured (British Columbia, 1998). This can be advantageous in situations where periodic flooding might carry away a conventional gage station or water quality concerns (e.g., pH extremes or metals) might affect the longevity or reliability of the recording device. Accuracy can be affected if environmental conditions (i.e., temperature, pressure, humidity) change the travel speed of the sound wave.

Submersible pressure sensors measure water stage with a pressure transducer mounted at a fixed depth in the water column. The sensor transmits an analogue or digital signal to the data logger through underwater conductors. A submersible pressure sensor also, generally, has a vent tube that allows the sensor to equilibrate itself to changes in barometric pressure. Submersible pressure sensors are relatively inexpensive, easy to install, and accurate. Analogue sensors can have an accuracy as good as 0.1 percent and digital sensors can be as accurate as 0.02 percent or better. Submersible pressure sensors typically have to be replaced if leaks develop; generally the electronics will be damaged beyond repair (British Columbia, 1998). Submersible pressure sensors are not affected by wind, turbulence, floating foam, or debris.

Pressure measurement, or bubbler, sensors are highly accurate digital sensors which measure the gas pressure required to generate a bubble at the end of a submerged orifice line. The pressure required to create the bubble is proportional to the water head above the orifice. Bubbler sensors cost less than submersible digital sensors and the only component in the water is the low cost orifice line. The sensor and the pressure source, nitrogen tank or battery compressor, are located in a shelter outside the channel. The bulky pressure tank is the main disadvantage to bubbler sensors; accuracy is similar to submersible digital sensors (British Columbia, 1998). Bubbler sensors are also not affected by wind, turbulence, floating foam, or debris.

Graphic Recorder

Graphic recorders chart a continuous trace of water stage with respect to time. Stage is recorded on a strip-chart or drum recorder with a pen or pencil attached to the gage-height element.

Most graphic recorders can record an unlimited range by a stylus reversing device or by unlimited rotation of the drum. Strip-chart recorders can be operated for several months between servicing. These types of recorders are extremely practical and cost effective at mine sites that often require monitoring of stream flow at remote locations in upper portions of a watershed or on important tributaries entering a site. Drum recorders need to be serviced weekly (Buchanan and Somers, 1982).

3.2 WEIRS

Weirs are the simplest, least expensive, and probably the most common type of device for measuring open channel flow. A weir is simply an obstruction or dam built across an open channel. The weir basin is formed by partial impoundment of water behind the weir face. The impoundment is only partial because water will continue to flow over the weir crest, the top edge of the weir plate. Typically water flows over the weir crest through a notch cut in the center of the weir crest. The notch can be V-shaped, rectangular, or trapezoidal (Grant and Dawson, 1997). Weirs are named for either the shape of the weir notch, as in ‘sharp-crested weirs’, or for the shape of the flow control section, as in ‘broad-crested weirs’. Both types are discussed in subsequent sections.

Weirs can be temporary or permanent measurement fixtures. Portable sharp-crested weirs may be used to measure small flows in earthen channels or lined tunnels. A simple weir for measuring flows in small earthen channels can be constructed from a stiff piece of metal cut in the shape of, but somewhat larger than, the channel cross section. A carefully cut weir notch is located along the top edge of the metal sheet. The metal sheet is forced into the channel bottom and sides, perpendicular to the direction of flow. The crest is adjusted until level. Portable long-throated flumes can be used at sites where insufficient head exists for sharp-crested weirs (see Section 3.3). In larger channels, weir plates are installed in bulkheads that have been sealed and sandbagged into place to prevent shifting as water pressure builds up behind the weir plate.

The stream of water leaving the weir crest is called the nappe. Proper measurement conditions occur when the nappe flows ‘free’ over the weir crest. Free flow, or critical flow, occurs when the nappe is thrown clear of the weir face and air flows freely under the nappe, and between the nappe and the weir face. Weirs provide accurate discharge measurements only within flow ranges specified by the size and geometry of the weir notch or crest. When the downstream water level rises to a point where air no longer flows freely beneath the nappe, the nappe is not ventilated and accuracy of the discharge measurement suffers because of low pressure beneath the nappe. Weir measurements are not usable when the downstream water level submerges the weir crest (Grant and Dawson, 1997).

The actual measuring point is located upstream of the weir plate in the weir basin. A staff gage is commonly used to measure the head (height of water above the crest) at a point in the weir basin upstream from the point where drawdown begins. Drawdown, or surface contraction, is the slight lowering of the water surface as the water approaches the weir. Drawdown typically begins at a distance of about twice the elevation head on the crest upstream of the weir. The gage should be situated a distance upstream of the weir equal to four times the maximum head expected over the weir (Grant and Barnes, 1997). Measurement accuracy can be enhanced by using a recording gage situated in a stilling well, instead of a staff gage in the weir basin (BOR, 1997).

3.2.1 Siting Criteria for Weirs

Weirs should be sited in a straight reach of the channel, normal to the line(s) and direction of flow. The weir crest must be level and the bulkhead plumb. Adequate cut-off walls are tamped in place to prevent water from undermining the weir structure. The stream reach or channel selected must allow positioning of the weir so that all stream flow is channeled over the weir crest. Flow undermining the weir structure can cause relatively severe errors in the discharge measurement, especially during low flow conditions. The average width of the approach channel should approximate the width of the weir box for a distance of 10 to 20 feet upstream for small weirs and greater than 50 feet for the larger structures. This insures that flow entering the weir structure is uniform.

Weirs are relatively easy to construct and maintain, and measurements are accurate as long as the proper flow conditions and channel dimensions are maintained. Weirs are not suitable for flat sloped channels that will not generate enough head loss for a free flowing nappe. Weirs are also not suitable for water carrying significant loads of silt or other suspended solids, unless the weir is designed such that solids can be periodically flushed out through the bottom of the weir. Otherwise, deposition of suspended solids in the weir basin will alter flow conditions and a loss in measurement accuracy will be realized. (Grant and Dawson, 1997). Other specific limitations are discussed under the specific weir types.

3.2.2 Sharp-Crested Weirs

A sharp-crested weir has a blade with a sharp upstream edge (Brooks et al., 1994). Passing water only touches the thin upstream edge of the blade; the nappe clears the remainder of the crest (Brooks et al., 1994). The traditional sharp-crested weirs used for measuring discharge are: rectangular weirs, V-notch weirs, and Cipolletti weirs (Figure 3-1) (BOR, 1997).

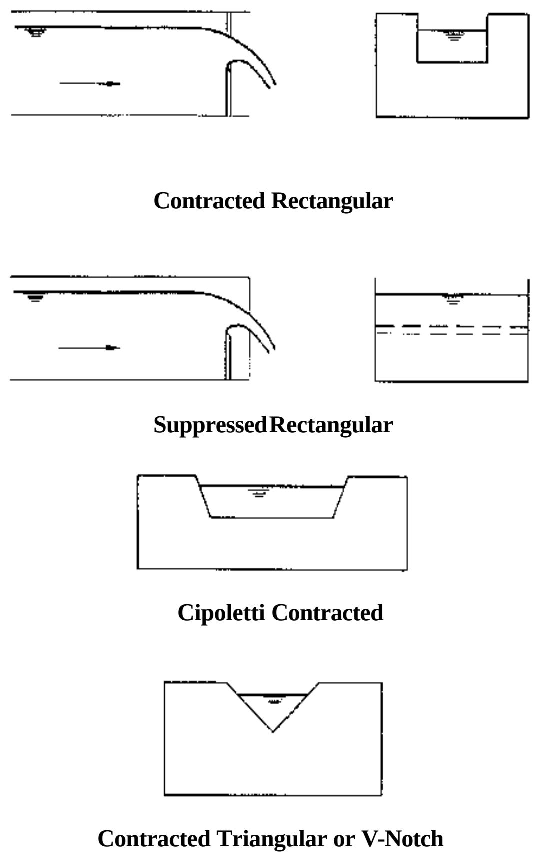

Figure 3-1. Sharp-crested Weirs (BOR, 1997)

Sharp-crested weirs are designed such that the minimum distance of the sides of the weir from the channel banks is at least twice the expected head. The crest of the weir should be at least twice the expected head above the bottom of the weir basin (Grant and Dawson, 1997). The downstream water surface should always remain at least 0.2 feet below the V-notch or crest. Discharge readings should be discarded if the contraction is not springing underneath for the entire length of the nappe (Roberson et al., 1988).

BOR (1997) identifies 12 necessary conditions for accurate flow measurement using sharp-crested weirs.

C The upstream face of the weir plates and bulkhead must be plumb, smooth, and perpendicular to channel flow.

C The weir crest needs to be level for rectangular and trapezoidal shapes. The bisector of V-notch angles must be plumb.

C The edges of the weir opening must be located in one plane. The corners of the weir opening must have proper specified angles.

C The top thickness of the crest and side plates should measure between 0.03 and 0.08 inch.

C All weir plates need to have the same thickness over the entire overflow crest boundary. Plates thicker than 0.08 inch should be beveled to an angle of at least 45 degrees on the downstream edge of the crest and sides. The downstream edge of V-notches should have a 60 degree angle to prevent water from clinging to the downstream face of the weir.

C Upstream edges must be straight and sharp. Burrs and scratches should be removed by machining or perpendicular filing; abrasive cloth or paper should not be used.

C The bottom edge plates and upstream fastener projection should be located at least the distance of two measuring heads from the crest. All upstream faces must be free of oil and grease.

C The overflow sheet or nappe touches only the upstream faces of the crest and side plates.

C The weir head measurement is the difference in elevation between the crest and the water surface at a point located upstream. The upstream point is a distance equal to four times the maximum expected head on the weir.

C The weir head measurement should be at least 0.2 feet to prevent the overflow sheet from clinging to the downstream weir face.

C The weir approach should be kept clear of sediment deposits and other debris.

The following sections describe common sharp-crested weirs and include an equation for calculating discharge from each. A range of measurable flow is presented for the smallest recommended design for each of the sharp-crested weirs, as well as a maximum flow for the largest structure of each type. The minimum range is presented under the assumption that discharges from mine sites are typically small and diffuse. The reader is referred to Grant and Dawson (1997) for more specific design factors, measurement ranges and values for the discharge equation constants for the three types of sharp-crested weirs presented.

Rectangular Weirs

Rectangular weirs have vertical sides and a horizontal crest (Brooks et al., 1994). A crest length of one foot is the minimum recommended for a rectangular weir since V-notch weirs can more accurately measure the same flow rates as rectangular weirs smaller than one foot. The minimum recommended crest length of one foot generally corresponds to a minimum flow of 0.286 cfs (128 gpm), assuming an elevation head of 0.2 feet, and a maximum flow of 1.06 cfs (476 gpm) with a head of 0.5 feet. Rectangular weirs can be designed to measure flows up to 335 cfs (150,000 gpm), assuming full end contractions, a crest length of 10 feet and head of 5.0 feet (Grant and Dawson, 1997).

The equation commonly used for obtaining actual discharge is (Grant and Dawson, 1997):

$$Q = K(L - 0.2H)H^{1.5}$$

where:

Q	=	flow rate
K	=	constant depending on units
L	=	crest length of weir
H	=	head on the weir

V-Notch Weirs

Sharp-crested V-notch or triangular weirs are used in situations where precise measurements of low flows are required. V-notch weirs are effective for low flow measurement because this type of weir has no crest length and requires less elevation head for the nappe to spring free of the crest. The minimum elevation head on a weir of this type is 0.2 feet with a maximum of 2.0 feet. A small V-notch weir with a notch angle of 22 ½ degrees can measure flows ranging from 0.009 cfs (3.99 gpm) at a head of 0.2 feet, up to 2.81 cfs (1,260 gpm) at a head of 2.0 feet. A notch angle of 120 degrees can measure flows up to 24.5 cfs (11,000 gpm) at a head of 2.0 feet (Grant and Dawson, 1997).

The discharge for a free flowing V-notch weir is given by (Grant and Dawson, 1997):

$$Q = KH^{2.5}$$

where:

Q = flow rate
K = a constant defined by the angle of the notch and units of measurement
H = head on the weir

Compound Weirs

Compound weirs are often used in situations where a V-notch weir could handle the normal range of flow but measurement of occasional larger flows would require a rectangular weir. The two profiles, rectangular and V-notch, can be combined to form a compound weir. Compound weirs accurately measure flow whether the weir is functioning as a V-notch or a rectangular weir. The problem, however, with compound weirs is accurate measurement in the transition between V-notch and rectangular weir behavior. Thin sheets of water will begin to flow over the rectangular weir crest in an unpredictable manner when discharge begins to exceed the capacity of the V-notch. This problem can be minimized if the sizes of the V-notch and rectangular sections are selected such that discharge measurements in the transition zone are of minimal importance. Discharge over a compound weir is calculated by applying the standard discharge equation for each segment of the weir to the head on that segment of the weir (Grant and Dawson, 1997). Compound weirs can be useful at mine sites simply because they accommodate a wide range of flows; the V-notch portion can accurately measure fall and winter low flows while the rectangular portion, plus the V-notch, provides accurate measurement of spring peak flows.

Trapezoidal (Cipolletti) Weirs

Trapezoidal weirs are similar to rectangular weirs except that the sides incline outwardly, not vertically. When the sides have an outward inclination of 1 horizontal to 4 vertical, the weir is known as a Cipolletti weir. Compared to a rectangular weir, the discharge equation is simpler because no correction factor is included for the crest width; discharge occurs as if the end contractions are suppressed. Trapezoidal weirs have a slightly greater measurement range, although measurement accuracy is less than would be obtained from a V-notch or rectangular weir. The accuracy of the Cipolletti equation is reported by BOR (1997) to be within ±5 percent of actual discharge. The smallest recommended trapezoidal weirs with a crest length of one foot has a measurement range between 0.301 cfs (135 gpm) at a head of 0.2 feet and 1.19 cfs (534 gpm) at a maximum head of 0.5 feet. A large trapezoidal weir with a crest length of 10 feet can measure flows up to 376 cfs (169,000 gpm) at a maximum head of 5.0 feet (Grant and Dawson, 1997).

The equation for calculating discharge using a free flowing Cipolletti weir takes the form of (Grant and Dawson, 1997):

$$Q = KLH^{1.5}$$

where:

Q = flow rate
K = constant depending on units
L = length of the weir crest
H = head on the weir

3.2.3 Broad-Crested Weirs

A broad-crested weir has a flat or broad surface over which the stream discharge flows. Broad-crested weirs are used much less frequently than sharp-crested weirs and are often pre-existing structures: dams, levees, and diversion structures. Broad-crested weirs are commonly used when sensitivity to low flows is not critical and where sharp crests could be dulled or damaged by sediment or flowing debris (Brooks et al., 1994). Flumes, however, are generally preferable for measuring debris and sediment-laden flows because broad-crested weir accuracy will be diminished by sediment accumulation upstream of the weir face.

True broad-crested weir flow occurs when the upstream vertical head above the crest is between the limits of one-twentieth to one-half of the crest length in the direction of flow (BOR, 1997). Sharp-crested weirs are preferable to broad-crested weirs for low flow measurement; however, under moderate to high discharges, the accuracy of a broad-crested weir approaches that of a sharp-crested weir, while maintaining several advantages (BOR, 1997):

- Broad-crested weirs can be computer calibrated.
- Broad-crested weirs should be considered when rust, abrasion, or impact might cause maintenance problems for sharp-crested weirs.
- Specially shaped broad-crested weirs can be designed to fit complicated channel cross-sections.

- Broad-crested weirs pass sediment and debris better than sharp-crested weirs, but can accumulate sediment upstream of the weir face.

- Broad-crested weirs can be submerged between 80 and 90 percent without affecting the measurement, depending on the shape of the downstream transition in the channel.

Broad-crested weirs are hydraulically similar to long-throated flumes. Computer calibrations of broad-crested weirs use the same principles and theories developed for long-throated flumes (*see* Section 3.3).

3.3 FLUMES

A flume is an artificial open channel constructed to contain flow within a designed cross section and length (Brooks et al., 1994). Flumes do not impound water like weirs, rather they restrict the channel area or change the channel slope to increase flow velocity and change the level of water flowing through the flume (Grant and Dawson, 1997). Flumes are typically constructed in streams with channel characteristics such that the natural stage-discharge relationship is subject to changing channel morphology, or is insensitive (Kilpatrick and Schneider, 1983). Flumes are well-suited to small flashy streams where current-meter discharge measurements are impractical due to rapid changes in stage. Flumes are also used in situations where existing channel head loss is too small to permit use of a weir or when significant quantities of sediment or solids must pass through the measurement device. The high velocity of flow passing through the flume keeps solids in suspension and functions as a self-cleaning mechanism (Grant and Dawson, 1997).

Flumes are commonly designed with a contraction in channel width and/or a drop or steepening of bed slope to produce critical or super-critical flow in the throat of the flume (Figures 3-2 through 3-4). The throat of the flume is the region where contraction occurs. The increase in slope, narrowing of the channel, or a combination of the two increases flow velocity to a value greater than the critical velocity for the discharge(s) of interest. To satisfy the continuity equation, depth of flow must decrease when a given quantity of water is discharged at a higher velocity. Critical flow and depth can only occur in a previous sub-critical channel by introduction of external processes (i.e., steepening of slope or constriction) that force the flow to pass through the critical region (Grant and Dawson, 1997). A hydraulic jump will typically occur at the point where flow passes from critical back into the sub-critical region and is visually observed as a wave preceding a return to sub-critical depth and velocity. The hydraulic jump may occur at the end of the constriction or at the point when channel slope becomes shallower. The hydraulic jump is the release of specific energy generated by inducing critical and super-critical flow.

The relation between the depth of water measured at a point upstream of the water surface drawdown and discharge is a function only of the configuration of the flume (Kilpatrick and Schneider, 1983), and this relation can be determined prior to installation. In situations where critical depth cannot be achieved, head must be measured in both the approach section and in the throat in order to determine the discharge rate (Grant and Dawson, 1997).

3.3.1 Siting Criteria for Flumes

Once the decision has been made that a flume is the appropriate measuring device for a site, the decision must be made as to whether to use a critical flow flume or a super-critical flow flume. Either type of flume will transport debris of considerable size without deposition in the structure. Excessively large rocks may become deposited at, or upstream from, the critical depth section of either critical or super-critical flow flumes. If this occurs in a critical flow flume, the discharge rating will change since head is measured upstream of the critical flow section and a large, solid object in the flow path may affect the depth of water. Super-critical flow flumes, such as the San Dimas flume, should be selected for sites where this is likely to happen. This type of flume measures head downstream of the critical depth section and less likely to be affected by flow disruptions above the critical depth section.

A critical-flow flume should be selected if the flume can pass the transported sediment load. The discharge rating for a critical-flow flume is more sensitive than the discharge rating for a super-critical-flow flume. The HS, H, and HL flumes have the smallest capacities of the critical flow flumes and have relatively high precision of measurement. These flumes are used extensively in small watershed research studies. The Parshall flume is generally selected for all other situations where the use of a critical-flow flume is desired. These flume types will be described later.

When the flume type and size are selected for the expected flow conditions, the flume must be fitted for optimum compatibility with the natural channel. Four factors must be considered in the precise fitting and placement of flumes:

- Channel characteristics.
- Range of discharge to be gaged.
- Desired precision of measurement.
- Maximum allowable backwater.

Flumes should not be installed too close to reaches with turbulent, surging or unbalanced flow, or in a stream reach with a poorly distributed velocity pattern (i.e., unequal and non-parallel lines of flow). Any of these flow conditions in the reach upstream of the flume may cause large errors in discharge measurements. Flumes should be placed in reaches with tranquil flow, defined as reaches with fully developed flow in long straight, mildly sloped channels that are free of curves, projections, and waves

(BOR, 1997). As a general rule, the approach channel should be a distance equal to 40 times the hydraulic radius, or 10 times the channel width at the water surface (BOR, 1997). Hydraulic radius is the cross-sectional flow area divided by the wetted perimeter.

The velocity of the approach channel should exceed 1 foot per second to discourage aquatic pests, insects, and sediment deposition (BOR, 1997). Approach channel flow with a Froude number less than or equal to 0.5 (sub-critical flow) over the entire range of expected discharges will prevent waves from forming and interfering with head measurement (BOR, 1997). Additionally, the channel reach selected for flume placement should have a stable and consistent bottom elevation.

A common failing in siting a flume is incorrect vertical placement. Excessive downstream channel scour and erosion can occur if the flume is placed too high in the channel. Furthermore, if the flume is placed too low, excessive backwater may cause submergence at higher flows. If the user is unsure about the proper size flume for a particular channel, it is generally better to select a flume that may be too big rather than one that is too small. An undersized flume can result in excessive backwater with frequent overtopping and possible scour around the edge of the flume. However, all flumes represent a compromise between measurement sensitivity (i.e., precision) and accuracy over the entire flow range.

3.3.2 Long-Throated Flumes

Long-throated flumes are common water measuring devices because they are easily fitted into a wide variety of channel shapes, ranging from simple to complex. Long-throated flumes have numerous advantages over other measuring devices, including long-term accuracy, technical performance, design, and calibration.

Long-throated flumes constrict the channel to cause critical flow; channel steepening is not necessary. A simple type of long-throated flume consists of a flat raised sill or crest across a trapezoidal channel. The approach ramp transitions from the approach channel invert. The crest drops vertically back to the downstream channel invert. Figure 3-2 is an illustration of a flat-crested, long-throated flume.

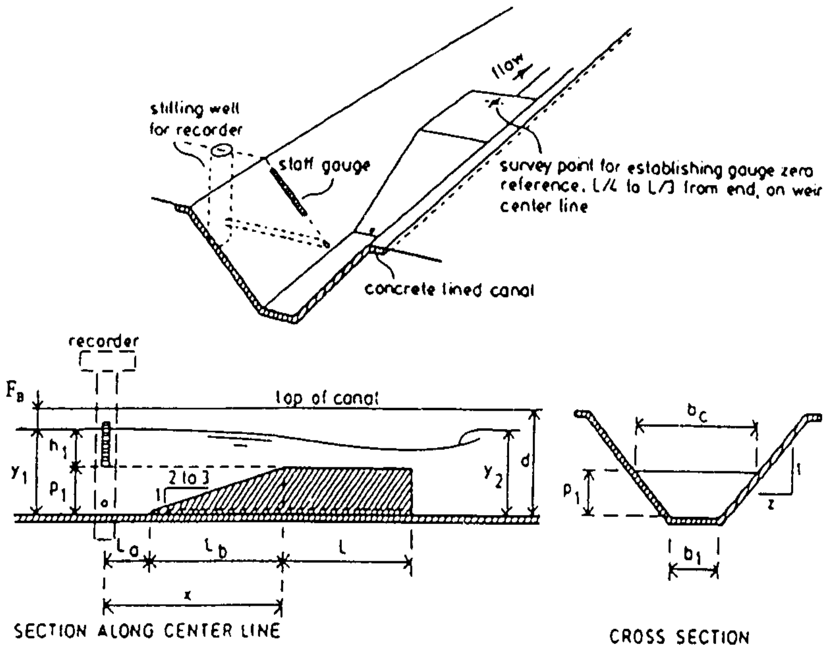

Figure 3-2. Flat-crested, Long-throated Flume (BOR, 1997)

BOR (1997) reports several advantages to using long-throated flumes for discharge measurements:

- Rating tables can be calculated with less than ±2 percent error, if critical flow occurs in the throat.
- Calculations can be made for any combination of prismatic throat and arbitrarily shaped approach channel.
- Long-throated flumes can be shaped to a wide range of channel shapes. The cross section of the flume’s throat can also be shaped to accurately measure a complete range of discharge, from low to high flows.
- Long-throated flumes can be portable and can fit conveniently into open channels.
- Long-throated flumes tend to pass floating debris and sediment.
- Specific rating tables can be developed using post-construction dimensions of the long-throated flume, assuming that the throat is horizontal in the direction of flow.

- Long-throated flumes tend to be more economical than other measurement devices.

- Long-throated flumes can be designed and calibrated using computer applications.

3.3.3 Short-Throated Flumes

Short-throated flumes are considered "short" because the flume is designed to control flow in a region that produces curvilinear flow. The overall specified length of the flume structure may be relatively long, however, the area of critical flow depth (i.e., the throat) is short. Accurate calibration of these types of flumes is difficult because calibration changes by site and level of discharge. For this reason, rating curves for short-throated flumes are usually determined empirically by comparing water depth at the measuring point with other more precise and accurate methods of determining discharge (e.g., current meters or other means of direct measurement). Parshall and Venturi flumes are two common examples of short-throated flumes.

Parshall Flume

The Parshall flume is a variation of the Venturi flume. A Parshall flume is characterized by a contracting inlet, a parallel-sided throat, and an expanding outlet, all with vertical walls (Brooks et al., 1994). Parshall flumes have a sharp drop in the slope of the floor through the throat in the flume. The break in floor slope causes the critical depth and location for measurement of vertical head to occur at the entrance to the throat. This feature creates a control that commonly requires that water depth (head) only be measured at a single point located near the approach to the throat. (Kilpatrick and Schneider, 1983). Parshall flumes have been developed and calibrated with throat widths ranging from 1 inch to 50 feet (Kilpatrick and Schneider, 1983). Figure 3-3 presents a plan and side view of a typical Parshall flume.

Parshall flumes can measure flows under submerged conditions, an advantage over the Venturi flume (Brooks et al., 1994). Submerged conditions occur when the water surface downstream of the flume is high enough to reduce the discharge. Parshall flumes typically contain two water-level recorders to measure discharge under submerged conditions, one located in the sidewall of the contracting inlet and one located slightly upstream from the lowest point of flow in the throat (Brooks et al., 1994). Both water-level recorders are used to determine the difference in vertical head between the two measuring points. This difference is then applied when calculating discharge under submerged conditions. Only the upper measuring point is used when calculating discharge under non-submerged conditions (Brooks et al., 1994).

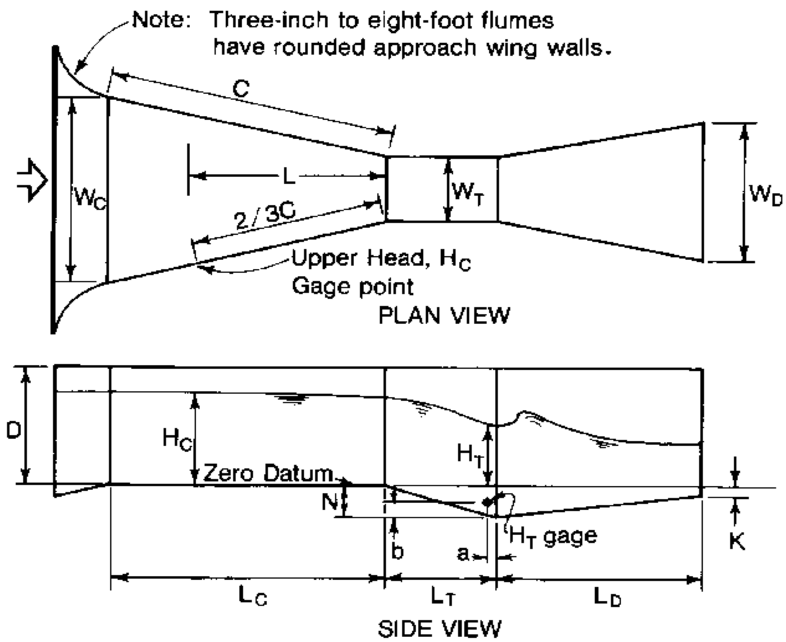

Figure 3-3. Configuration and Proportions for Parshall Flumes (Kilpatrick and Schneider, 1983)

The Parshall flume was developed primarily for use in irrigation canals, stream diversions or small routing channels. Recently, these flumes have been successfully used as gaging-station controls in natural streams. An advantage of the Parshall flume is that it will pass small- to medium-sized sediment without affecting the discharge rating curve and the accuracy of the measurement. The discharge rating will be affected by installing the flume with poor channel alignment and when there is an uneven distribution of stream flow entering the approach. The rectangular cross section makes the Parshall flume insensitive to low flows (Kilpatrick and Schneider, 1983). Under low-flow conditions, temporary V-notch weirs can be installed at the entrance to the flume throat to more accurately measure discharge (Kilpatrick and Schneider, 1983).

Parshall flumes have been constructed with throats ranging in width from 1-inch to 50-feet. Very small Parshall flumes have throat widths of 1, 2, or 3 inches and have minimum - maximum flow rates of 0.010 - 0.194 cfs (4.28 - 87.3 gpm), 0.019 - 0.478 cfs (8.55 - 215 gpm), and 0.028 - 1.15 cfs (12.6 - 516 gpm), respectively. Small Parshall flumes have throat widths of 6-inches through 8-feet, and large Parshall flumes have throat widths greater than 10-feet (Grant and Dawson, 1997).

Venturi Flume

A Venturi flume is any rectangular, trapezoidal, triangular, or other regular shape with a gradually contracting section that leads to a constricted throat (Brooks et al., 1994). The flume expands immediately downstream of the throat (Brooks et al., 1994). The floor of a Venturi flume is the same grade as the channel (Brooks et al., 1994). Stilling wells are located at the entrance and at the throat to measure head. The difference in head between the two wells is related to stream discharge.

Trapezoidal flumes are increasingly used to measure flows associated with hardrock mine discharges. The trapezoidal flume is designed to measure super-critical flows. The trapezoidal shape conforms to the natural shape of a channel, minimizing the required length of the transition section, as compared with a rectangular flume. Trapezoidal flumes require flow to transition between the trapezoidal channel cross-section and the rectangular flume cross-section. The walls of a trapezoidal flume slope outward to provide increased sensitivity to low flows while maintaining measurement of higher flows. Thus, trapezoidal flumes can measure a larger range of discharges than other types of flumes. Trapezoidal flumes also have a flat bottom. The flat bottom allows the flume to be placed directly on the channel bottom and permits the flume to pass sediment and other debris (Grant and Dawson, 1997).

Special Short-Throated Flumes

Many flumes have been designed to meet specific organizational needs and for special use situations, and are often termed *Special Flumes*. These flumes are commonly referred to as short-form or short-throated flumes. Two special flumes are discussed below, the H-type flumes, and the San Dimas flume. These flumes are extremely difficult to calibrate because of the sharp connection of the convergence and divergence of flows.

H, HS, and HL Flumes

The U.S. Natural Resource Conservation Service (NRCS), formerly Soil Conservation Service (SCS); developed HS, H, and HL flumes, or generally H-type flumes, for measuring intermittent run-off from small watersheds (Kilpatrick and Schneider, 1983). H-type flumes are commonly used to measure run-off from feedlots, infiltration areas, and low flows of streams in pollution abatement projects. H-type flumes can measure a wide range of flows with reasonably good accuracy and are simple to construct and install. The wide measurement range makes these flumes particularly useful for measuring drainage water.

H, HS, and HL type flumes have converging vertical sidewalls cut back on a slope at the outlet to provide a trapezoidal projection. These sidewalls promote self-cleaning of the flume floor. The flumes have a level floor that becomes extremely narrow at the downstream end. This narrow area was designed to increase the sensitivity of the discharge rating curve, and thus, increasing the precision of the discharge measurement (Kilpatrick and Schneider, 1983). A free fall is used to establish critical flow at the downstream end of the flume. While the flume is designed for use under free fall conditions, submergences of up to 50 percent do not significantly affect the head versus discharge relationship (Kilpatrick and Schneider, 1983). Vertical head is measured upstream from the end of the flume in the converging approach section (Kilpatrick and Schneider, 1983).

The three flumes are similar in general configuration but have different proportional dimensions. The HL flume has the greatest capacity, where the letter L is an indication of a large capacity. Conversely, the HS flume has the smallest capacity, where the letter S is an indication of small capacity (Kilpatrick and Schneider, 1983). HS flumes were designed to measure small discharges with maximum flow rates between 0.085 and 0.821 cfs (38.1 to 368 gpm). H flumes were designed to measure medium discharges with maximum flow rates between 0.347 and 84.5 cfs (156 to 37,900 gpm). HL flumes were designed to measure larger flows, up to 117 cfs (52,600 gpm) (Grant and Dawson, 1997). Typical HS, H, and HL flumes are presented in Figure 3-4.

San Dimas Flume

A San Dimas flume has the same function as a broad-crested weir with the exception that flow is constricted from the side, rather than the bottom (Brooks et al., 1994). This flume has a converging approach reach with a flat floor. A hump is located at the downstream end of the approach reach; this is the critical depth cross section. The super-critical reach, downstream from the hump, has a rectangular cross section with a 3 percent slope. Head is measured in the super-critical-flow reach of the flume, three feet downstream from the critical depth cross section. San Dimas flumes are very insensitive to low flow conditions and exhibit very poor accuracy. This is because of the rectangular shape and because the measurements are made from a section of the flume with super-critical flow. San Dimas flumes can be operated in conjunction with sharp-crested weirs to measure low flow conditions. Provisions, however, must be made to bypass high flows around the sharp-crested weir because sediment loads can damage the crest blade.

Small San Dimas flumes can be designed to measure flows with a minimum head of around 0.1 feet and minimum discharges of 0.16 cfs (71.8 gpm). Large San Dimas flumes can be designed to measure flows up to 300 cfs (134,625 gpm) (Kilpatrick and Schneider, 1983). The San Dimas flume is best used to measure debris-laden flows in mountain streams under relatively high stream flow regimes. The side constriction prevents sediment deposition and relative high flow velocities keep the flume clean of debris (Brooks et al., 1994).

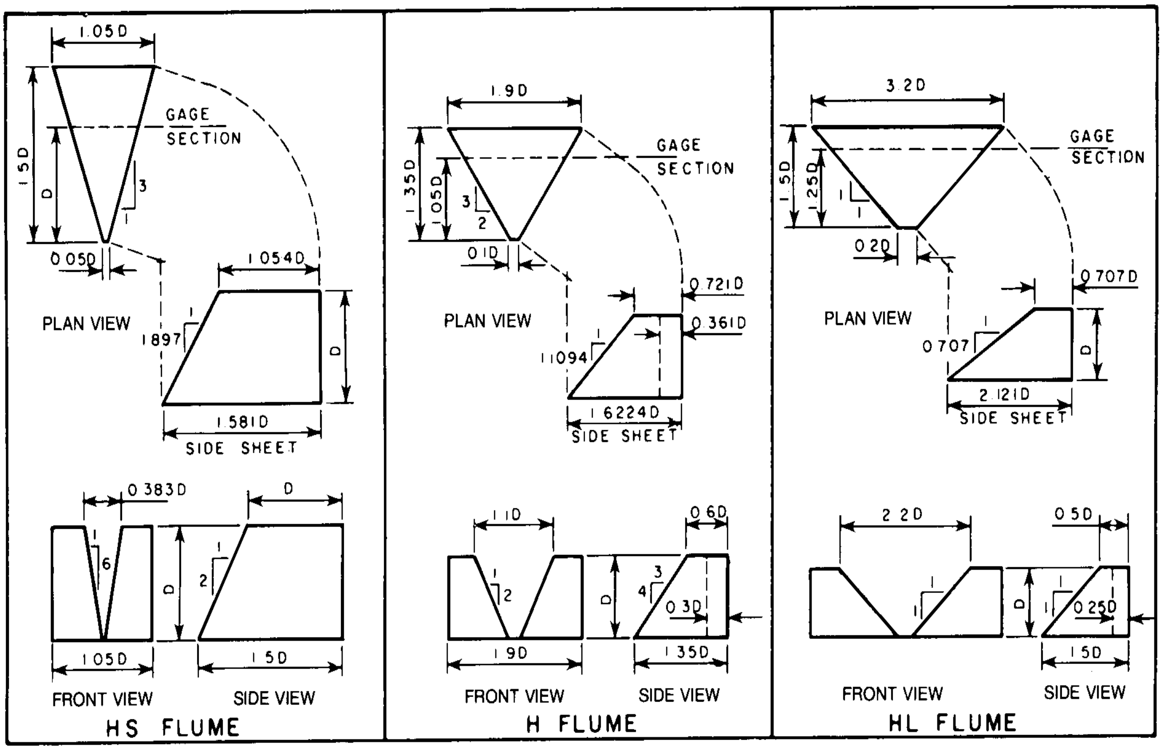

Figure 3-4. Configuration and Proportions of Type Hs, H, and Hl Flumes (BOR, 1997)

Cutthroat Flumes

The cutthroat flume gets its name from the absence of a parallel-wall throat section. This flume is a simple, flat-bottom device that can be placed directly on an existing channel without further excavation. Cutthroat flumes work well in flat-gradient channels where measurement conditions occur under both free and submerged flow conditions. Free flow conditions are preferable as only one head measurement needs to be taken, upstream of the constriction. Submerged flow requires measurements of both upstream and downstream head. The cutthroat flume is dimensionally defined by a characteristic length and throat width. All other flume dimensions can be derived from length and width (Grant and Dawson, 1997). Grant and Dawson (1997) present common sizes of cutthroat flumes; other sizes can be interpolated from these.

Cutthroat flumes have the advantage of ease of design, construction, calibration, and installation. However, the rectangular cross-section negatively affects measurement accuracy when trying to measure flows lower than those for which the flume was designed.

3.4 CURRENT METERS

Current meters measure flow velocity at specific horizontal and vertical points within a cross section of a channel or stream and therefore are less accurate than flume or weir measurement methods when measuring uneven flow channels. Each measured velocity point is assigned to a small portion of the cross-sectional flow area, where the computed discharge for a given point is the measured velocity multiplied by the cross-sectional area represented by that point measurement. This method results in several partial discharges being computed across a single cross section of the channel being measured. The total discharge for the cross section is the sum of the partial discharges. Velocity data is typically collected over the expected range of total discharges.

3.4.1 Siting Criteria for Current Meters

Current meter gaging stations should be situated in straight, uniform channel reaches with smooth banks and stable beds. The gaging station should be sited as far as possible from areas of disturbance in the flow pattern. Flow disturbance diminishes the reliability of the relationship between gage height and discharge. If current meters are used to develop a stage-discharge relationship, this rating curve should be frequently recalculated for channels with unstable beds, changing bed and bank conditions, or with large amounts of aquatic vegetation. These factors all change the relationship between the stage height of water and the cross sectional area of the channel.

3.4.2 Types of Current Meters

Several different types of current meters are used in water measurement: anemometer and propeller velocity meters; electromagnetic velocity meters; Doppler velocity meters; and optical strobe velocity meters. These meters are described in the following sections. The anemometer and propeller type meters are the most commonly used devices and are the most readily available.

Anemometer and Propeller Velocity Meters

Anemometer and propeller velocity meters measure velocity with anemometer cup wheels or propellers. The Price current meter and the smaller pygmy meter modification are the most common examples of this type of meter. These meters provide a small electronic pulse that is transmitted to a small head-set worn by the user. The meter can be set to produce a countable pulse for each complete revolution or for every 10 complete revolutions, depending on the range of velocity of the flow being measured. These types of velocity meters do not measure the direction of velocity, restricting their use to sites with relatively laminar, and critical or sub-critical flow regimes (BOR, 1997).

Electromagnetic Velocity Meters

Electromagnetic current meters produce and log voltage that is proportional to the velocity of the flow. In this manner, the meter provides a direct reading of velocity. The user is not required to count revolutions of the meter, as is required with anemometer and propeller type velocity meters. Electromagnetic velocity meters are able to measure cross sectional and directional flows (BOR, 1997). These meters cannot be used near metallic objects.

Doppler Type Velocity Meters

This type of current meter determines velocity from measurements of changing source light or sound frequency from the frequency of reflections from moving particles (e.g., sediment, or air bubbles). Lasers are used as the source light with laser Doppler velocimeters (LDVs); acoustic Doppler velocimeters (ADVs) use sound. Vertical current profiles can be measured using acoustic Doppler current profilers (ADCPs). ADCPs measure average velocities of selected size cells in a vertical series. ADCPs are typically used to measure deep flow and currents in reservoirs, oceans, and large rivers (BOR, 1997). Doppler type velocity meters can measure velocity components from multiple directions.

Optical Strobe Velocity Meters

Optical strobe velocity meters are comprised of mirrors mounted around a polygon drum. The drum can be rotated at precisely controlled speeds. Light from the water surface is reflected into the meter's lens system by the mirrors. The rate of drum rotation is controlled by the user who is looking at the reflected images through an eyepiece. The images become steady and the water surface appears to be still when the drum is rotated at the proper speed. Surface velocity is calculated from the rotational speed of the drum and the distance from the mirrors to the water surface. Velocity is translated into discharge by applying a coefficient and multiplying by the cross-sectional area of that particular reach (BOR, 1997).

The optical strobe velocity meter can be used to measure flood flows, high velocity flows, and debris laden flows since the gage does not require any parts to be immersed in the current. The accuracy of this meter is affected by the proper selection of the coefficient, available from standard tables, because the meter only measures the velocity of the water surface (BOR, 1997).

3.4.3 Methods to Determine Flow Velocity

Several different methods can be used to measure mean velocities with a current meter. The methods differ in the specific depths and number of depths that velocity measurements are taken at a measuring point along a channel cross section. The choice of the method used is dependent on the objectives of the measurement, the relative depth of water in the cross section, and the type of channel being measured. These methods are summarized below:

Two-point method -- The two-point method relies on velocity measurements taken at 0.2 and 0.8 of the total depth from water surface. Flow velocity for the measurement point is taken as the average of the two measurements. The use of this approach is encouraged because it increases the accuracy of the results and is based on known hydraulic properties that typically exist in open channels. This method should not be used at sites with water depths less than two feet (BOR, 1997).

Six-tenths-depth method -- The six-tenths-depth method is generally used when flow depth is less than two feet. This method provides satisfactory results by measuring velocity at 0.6 of the total depth from the water surface (BOR, 1997).

Vertical velocity-curve method -- The velocity profile is defined by taking velocity measurements along a vertical profile. The accuracy of the computed mean velocity is determined by the number of velocity measurements obtained. This approach is highly accurate, but time consuming and expensive (BOR, 1997).

Subsurface method -- The subsurface method requires that velocity be measured near the water surface. The measurement is multiplied by a coefficient ranging between 0.85 and 0.95, depending on factors such as water depth, velocity range, and streambed characteristics. The accuracy of this method depends upon the selection of the proper coefficient (BOR, 1997).

Depth integration method -- The depth or traveling integration method measures velocity at various points along a vertical line. Measurements are taken as the meter is slowly and uniformly raised and lowered two to three times throughout the range of water depth. Flow velocity is the average of all observations. The depth integration method is not accurate and should only be used for comparisons or screening-level estimates (BOR, 1997).

3.4.4 Computing Stream Discharge

Discharge is calculated from current meter data using the velocity-area principle, "total discharge is the summation of all computed partial discharges". A partial discharge is defined by:

$$q_n = \overline{V_n} a_n$$

and total discharge is expressed as:

$$Q = \sum_{1}^{n} (\overline{V_n} a_n)$$

where:

q = discharge for a partial cross-sectional area in cubic feet per second
Q = total discharge, cubic feet per second
V_n = the mean velocity of the partial cross-sectional area, feet per second
a_n = area of the partial cross section, feet squared

Partial discharge can also be calculated using the simple average method, midsection average method, or Simpson's parabolic rule. These approaches are discussed extensively by BOR (1997), and other hydrology texts.

3.5 ACOUSTIC VELOCITY METERS

An acoustic velocity meter (AVM) measures the velocity of flowing water by means of a sonic signal. AVMs work on the principle that a high frequency acoustic signal sent upstream travels slower than a signal sent downstream. Average path velocity is calculated by accurately measuring the transit times of signals sent in both directions along a diagonal path (BOR, 1997). Average axial velocity is calculated from information on the angle of the acoustic path relative to the direction of flow (BOR, 1997). Meters of this type are useful for measuring discharge at streamflow sites where the relation between discharge and stream stage varies with time (e.g., variable backwater conditions) and when stream gradients are too flat to permit accurate measurements for slope computations.

The AVM is a non-mechanical, non-intrusive device capable of measuring lower velocities than a current meter. AVMs provide a continuous and reliable record of water velocities over a wide range of conditions, subject to four constraints.

1. Accuracy is reduced and performance degraded if the acoustic path is not a continuous straight line. The path can be bent by reflection if it passes too close to a stream boundary

or by refraction if the path passes through density gradients resulting from changes in salinity or temperature.

2. Signal strength is attenuated by particles or bubbles that absorb, spread, or scatter sound.

3. Changes in streamline orientation can affect system accuracy if the variability is random.

4. Errors relating to signal resolution are much larger for a single threshold detection scheme than for multiple threshold schemes.

AVM systems range from a simple velocity meter to complex computerized systems that collect and transmit real-time discharges. Site factors determine whether a single path is adequate or whether multiple paths are required.

3.5.1 Siting Criteria for Acoustic Velocity Meters

AVM systems can be used over a wide range of flows from low flow situations to sections where velocity is extremely fast. BOR (1997) describes a good AVM site as:

C A reach with a uniform velocity distribution and confined channel.

C The channel should be straight for 5 to 10 channel widths upstream and 1 to 2 channel widths downstream.

C The channel bottom should be relatively stable.

C The cross-sectional area and profile should be relatively consistent through the gaged reach.

Other site selection criteria include considerations of the limiting acoustic criteria, equipment requirements, and potential installation problems.

Data must be collected on stream cross section, water temperature, and salinity profiles. Other conditions that may affect AVM performance include: air entrainment; algae; moss; weed growth; and suspended sediment (Laenen, 1985). These data may need to be collected over time so that maximum temperature, salinity differentials, maximum suspended sediment concentrations and particle-size distribution; and maximum and minimum stages can be reliably estimated (Laenen, 1985). Temperature and salinity gradients are minor in many streamflow situations and data collection will be unnecessary.

Gradients would be expected in streams with slow moving or ponded water, downstream from tributary inflows, downstream from thermal discharges, and tidal reaches (Laenen, 1985).

AVMs cannot be used to compute velocity where large eddies persist in the stream, nor can they be used in reaches with extreme turbulence or other poor hydraulic measuring conditions (e.g., air and gas entrainment) (Laenen, 1985). Sources of air and gas entrainment include dam spillways, natural stream riffles, and decaying vegetation (Laenen, 1985).

3.5.2 Types of Acoustic Velocity Meters

Single-Path Acoustic Velocity Meters

Single-path AVMs function as flowmeters by calibrating the acoustic path velocity against mean channel velocity, estimated using standard stream gaging techniques (BOR, 1997). The angle between the acoustic path and the average direction of streamflow is normally between 30 and 60 degrees. The discharge rating procedure involves collecting data on stage-area relationships, acoustic path velocities, and mean discharge velocities for the expected range of flows and stages. The velocity rating is derived using a linear regression with instantaneous mean channel velocity as the dependent variable and acoustic path velocity as the independent variable (BOR, 1997). Discharge is estimated by multiplying the predicted mean channel velocity by the cross-sectional area at the gage site. Flow measurement accuracy is limited by the quality of data collected for the calibration ratings. Single-path AVMs can attain accuracies within ±3 percent of the actual discharge (Laenen, 1985).

Multipath Flowmeter

Multipath flowmeters use several acoustic paths which are mounted at various elevations throughout the measurement section. The velocity profile is established from the average axial velocity for each acoustic path. The velocity profile is numerically integrated over the channel’s cross-sectional area to determine the volumetric flow rate. The accuracy of a multipath flowmeter is relatively independent of the velocity profile (BOR, 1997). Integration errors often occur because velocities near the channel bottom and water surface cannot be measured because of acoustic interference. However, if properly used, multipath flowmeters can attain accuracies within 1 percent of actual discharge (Laenen, 1985).

3.6 TRACERS AND DYE DILUTION METHODS

Tracers injected into a stream behave in a similar manner as water particles traveling with the flow. The measurement of the movement of a tracer is essentially the same as measuring the movement of an element of fluid in the stream, taking into account the dispersion characteristics of the fluid. Most tracers used for measurement of stream flow are very conservative with respect to water (i.e., they flow and behave similarly to water molecules under conditions of flow, and do not have significant attenuation properties). After injection of a tracer to a stream, dispersion and mixing occurs as the tracer moves downstream (Kilpatrick and Cobb, 1985). Mixing and dispersion occur in three dimensions, vertical, lateral, longitudinal. Under most open channel flow conditions, an equal mixing of a conservative tracer is usually achieved first in the vertical direction, followed by equal mixing in the lateral (cross-stream direction) at a point further downstream. Longitudinal mixing in the downstream direction continues indefinitely because no boundaries are encountered in this dimension.

Figure 3-5 shows the typical response to the injection of a tracer into a flowing channel with downstream distance. After injection of a tracer, either as a slug or at a continuous rate, a response curve can be plotted at any downstream point by plotting tracer concentration against time. These response curves form the basis for determining stream characteristics including time-of-travel, dispersion, and discharge.

3.6.1 Siting Criteria and Sources of Error

The accuracy of open channel discharge measurements using tracers can be affected by the choice of the reach where measurements are taken. Specifically, backflow eddies can delay the dye and impede mixing. An ideal reach for tracer measurement will not contain large backflow eddies or stagnant pools. As with other methods, measurements should be taken in stream reaches that have steady uniform flow, no large eddies or deep pools, and measurable cross sections.

Accuracy is also sensitive to how well the tracer cloud's center of mass is determined with respect to time. The first and last observations of a cloud may be difficult to detect, and the center of mass may not be located in the time center of the cloud. Discharge measurement accuracy with tracers can approach ±1 percent with the use of expensive equipment such as multiport pop valves, turbulators, complex electrodes, and fluorometers (BOR, 1997). Discharge estimates can also be obtained with tracer methods. The least accurate tracer method would be to break a bottle of dye at an upstream station and estimate how long the center mass takes to pass by the downstream measuring station.

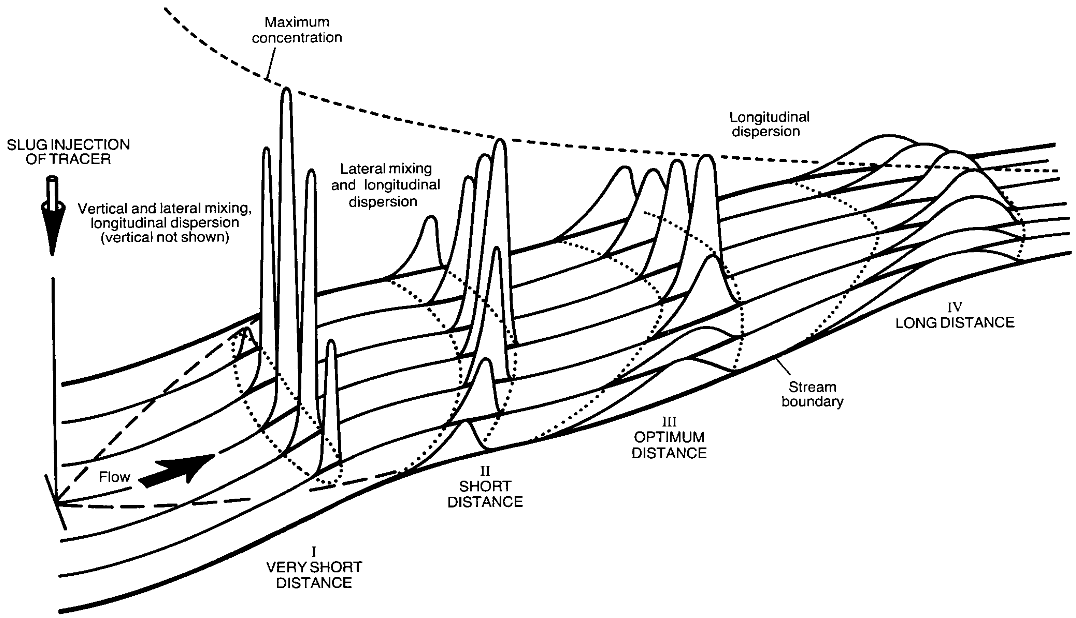

Figure 3-5. Lateral Mixing and Longitudinal Dispersion Patterns and Changes in Concentration Distributions from a Single, Slug Injection of a Tracer (Kilpatrick and Wilson, 1989)

3.6.2 Types of Tracers

A tracer is anything that mixes with water or travels with the flow of water. As previously indicated, an ideal tracer moves conservatively with respect to the water and exhibits no significant properties of attenuation or retardation with respect to flow. A tracer has to be detectable and measurable at downstream points. Tracers used in hydrologic studies include:

- Dyes of various colors.
- Chemicals such as fertilizer, salt, or gases.
- Radioisotopes.
- Heat.
- Traveling turbulent eddy pressure sequences.
- Neutrally buoyant beads.
- Floats.

Dyes and salts are the most convenient tracers for measuring discharge at mine sites. Salt tracer concentrations are determined by measuring the evaporated dry weight, through chemical titration, or by electrical conductivity. When salt solutions are used as tracers, chemical or conductivity methods are used for detection and concentration measurements. The salt-dilution method works well in small to medium sized turbulent streams. Large streams require excessive quantities of salt to significantly change electrical conductivity above background values.

Dye tracing involves introduction of dye into a water body followed by collection of water samples over time and space to measure the response. Response is a function of the dye concentration in the samples, as measured using a fluorometer (Wilson et al. 1986). Fluorometric procedures for dye tracing can be used to measure time-of-travel, dispersion, reaeration, and stream discharge. Dyes used as tracers include Fluorescein, Rhodamine B, Rhodamine WT, and Pontacyl Pink B. These dyes are all easily visible and/or detectable using fluorimetry in dilute concentrations. The Rhodamine dyes are considered nontoxic by the U.S. Food and Drug Administration. Rhodamine and Pontacyl Pink B are considered relatively stable and are resistant to fading and changes in their fluorimetric properties. They are also resistant to chemical changes by other waterborne constituents, and resist deposition onto flow surfaces, weeds, and sediments (BOR, 1997). Prior to using any dye for flow measurement, however, it is recommended that the selected dye(s) be tested with water and earth embankment samples for adsorption, chemical reactions, and fading before conducting the discharge measurement program (BOR, 1997). For example, these dyes can be affected under strongly acidic conditions caused by acid generating ores or waste rock. In addition, the precipitation of iron oxyhydroxides in streams that had been dissolved as a result of acid mine drainage can also affect fluorimeter readings. Under these conditions, the use of salt tracers would be recommended.

Dye tracing has two characteristics that make this technique favorable for measuring stream discharge. First, dye tracing has low detection and measurement limits. Fluorometers can measure dye concentrations down to one part per million (ppm) and detect dye down to one part per billion (ppb) (BOR, 1997). Second, measuring dye tracer concentrations is simple, relatively easy to apply in the field, and accurate with fluorometric techniques.

Kilpatrick and Cobb (1985) suggest that tracer methods can be particularly useful under the following flow conditions:

- Where it is difficult or impossible to use a current meter due to high velocities, turbulence, or debris.

- Where, for physical reasons, the flow is inaccessible to a current meter or other measuring device.

- Where, for some conditions, the rate of change of flow is such that the time to make a current-meter measurement is excessive.

- Where, the cross-sectional area cannot be accurately measured as part of the discharge measurement or is changing during the measurement.

3.6.3 Methods to Determine Stream Discharge

Two approaches can be used to measure discharge using dye or salt tracers (BOR, 1997; Kilpatrick and Cobb, 1985). The velocity-area method uses the time required for a tracer to travel down a known channel distance and then uses the average cross-sectional area for the reach to determine stream discharge. The dilution method measures stream discharge using the measured downstream concentration of a fully mixed tracer that is being added upstream at a constant rate (BOR, 1997).

Velocity-Area Method

Stream discharge is calculated using the velocity-area method as follows:

$$Q = \frac{AL}{T}$$

where:

Q = stream discharge, in cubic feet per second
A = average cross-sectional area of the reach length, in square feet
L = the length of the stream reach between detection stations, in feet
T = tracer travel time between the detection stations, in seconds.

Both salts and dyes can be measured using the velocity-area method; however, each requires different detection equipment. Dyes have the advantage of being visible, allowing for simpler measurements when fluorometers are not used.

Salt-Velocity-Area Method

The salt-velocity-area method is based on the fact that salt in solution increases the electrical conductivity of water (Kilpatrick and Cobb, 1985). This approach has the potential for higher accuracy and precision and has been successfully used in open channels and conduits. Sodium chloride

(NaCl) is typically the salt used in the tracer injection solution. Other halide compounds, such as lithium bromide (LiBr) or sodium bromide (NaBr), have been used in situations where high background concentrations of chloride in stream waters interfere with the conductivity measurement (Kimball, 1999). The salt concentration in the tracer solution must be high enough to significantly increase the electrical conductivity of the receiving water.

The method is employed by injecting the tracer solution into the receiving water upstream from the measurement reach. The measurement reach should be located a sufficient distance downstream from the injection point to allow for complete mixing of the tracer in the receiving water. This reach should be selected such that it is uniform and the channel-flow geometry can be defined exactly. A pair of electrodes is installed near the sides of the channel at both the upstream and downstream ends of the measurement reach. The two pairs of electrodes should be sited far enough apart, upstream and downstream, to allow accurate measurement of travel time between them. A central instrument records and graphs electrical conductivity at the electrode sites with respect to time. Electrical conductivity increases as the tracer cloud passes through the electrodes. Data are recorded and graphed by the central instrument. The time of travel is equal to the length of time required for the peak mass of the tracer cloud to pass through both sets of electrodes.

The salt-velocity-area method is highly accurate; however, special equipment (i.e., an electrode system) and experienced personnel are required to apply the method. Accuracy can be enhanced by selecting reaches where cross sections and reach length can be measured with relative ease.

Dye-Velocity-Area Method

Maximum accuracy from dye tracer solutions can be achieved using a fluorometer. The procedures are similar to the salt-velocity-area method except that a fluorometer, instead of the electrode system, is used to measure dye concentrations at a downstream cross-section. The American Society of Mechanical Engineers *Performance Test Codes* (1992) can be followed to achieve very accurate discharge measurements.

Dilution Method

Measurement of stream discharge by dilution methods depends on the determination of the degree of dilution of an added tracer solution by the flowing water. Stream discharge is calculated using the dilution method as follows:

$$QC_o + qC_1 = (Q + q)(C_2)$$

and stream discharge (Q) is solved using the following equation:

$$Q = q\frac{C_1 - C_2}{C_2 - C_0}$$

where:

- C_0 = background concentration of the tracer in the stream
- C_1 = concentration of the strong injected tracer solution
- C_2 = the concentration of tracer at the sampling station, after full mixing
- q = discharge of the strong solution injected into the flow

When using salt tracers, dry weight can be substituted for concentration values and the weight of water per second can be substituted for discharges (BOR, 1997). The dilution method is appealing because it does not require measurements of stream cross sections; however, possible tracer (salt or dye) losses may be a problem. Dye losses can generally occur when excessively long stream reaches are used, and when there is relatively high concentrations of suspended clays or organic particles that can absorb the dye (Kilpatrick and Cobb, 1985). Losses can also occur when significant concentrations of chemicals like chlorine are present that oxidize or quench the dye (Kilpatrick and Cobb, 1985).

The dilution method does require a sufficiently long flow length to ensure that there is complete mixing prior above the chosen sampling location. The length of stream required to provide complete mixing can be reduced by setting up a system to simultaneous inject the tracer at several points laterally across the stream or channel.